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STUDIES OF ANISOTROPIC PERMEABILITY WITH APPLICATIONS TO WATER REMOVAL IN FIBROUS WEBS
PART 1. EXPERIMENTAL METHODS, SHEET ANISOTROPY AND RELATIONSHIPS TO FREENESS.

J.D. LINDSAY AND P.H. BRADY

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J.D. Lindsay and P.H. Brady

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Part 1. Experimental Methods, Sheet Anisotropy and Relationships to Freeness.

Jeffrey D. Lindsay
Assistant Professor
Institute of Paper
Science and Technology
500 10th Street, NW
Atlanta, GA 30318

Paul H. Brady
Undergraduate Student
Auburn University
Textile Engineering Dept.
101 Textile Building
Auburn, AL 36849

ABSTRACT

An extensive set of data for in-plane and transverse permeability has been obtained. We focus on recent results for hardwood and softwood kraft pulps which are consistent with measurements in other pulp types. Anisotropic permeability data are discussed in terms of practical implications and theoretical considerations such as pore structure.

The new data give insight into two-dimensional flows which may occur in practical papermaking and nonwovens processes. The observed tendency for fiber networks to have high in-plane permeabilities is especially relevant in water removal processes. For example, in-plane flows can reduce the water removal capacity of a press. Saturated permeability data are also directly correlated with impulse drying performance. As a measure of water removal performance, saturated permeability data are much more relevant than freeness data.

A variety of factors can influence the saturated transverse or in-plane permeability of a fibrous network. We consider the effects of compression, fines content, basis weight, yield, and different disintegration and refining methods. In addition, the effects of hornification from drying and partial hornification from wet pressing were quantified. Partial water removal by pressing results in a change in pore structure, increasing the permeability of the resaturated sheet. This change is not due to true hornification, but may represent a temporary collapse of fibrils and rearrangement of fines. The permeability of a dried and resaturated sheet increased more than the permeability of a sheet formed from dried and reslushed fibers.

KEYWORDS
Permeability, flow through porous media, anisotropy, wet pressing, impulse drying, recycled fibers, hornification.

BACKGROUND

Darcian Permeability

Paper permeability is commonly expressed in terms of gas flow rates through a sheet. This practice is useful for comparing similar sheets, but does not truly characterize the interaction of flowing fluid with the porous structure and provides no direct information about flow in a wet sheet. The standard engineering definition of permeability provides a more useful parameter, though one less easily measured. The standard definition is based on Darcy's law (1), which, for one-dimensional flow, states that the velocity of fluid flow through a saturated porous medium is directly proportional to the pressure gradient:

$$v = \frac{K}{\mu}\frac{\Delta P}{L} \tag{1}$$

where v is the superficial velocity (flow rate divided by area), K is the permeability, μ is the fluid viscosity, and ΔP is the pressure drop in the flow direction across a distance L. The units of K are m^2. In Equation (1), the permeability is an empirical proportionality parameter linking fluid velocity to pressure drop and viscosity. For a homogeneous medium, K is not a function of ΔP, sample length, or viscosity, but is an intrinsic parameter describing the flow resistance of the medium. In a compressible medium, permeability will be a strong function of the degree of compression.

Importance of Permeability

Darcian permeability is commonly a fundamental parameter for processes involving fluid flow in fibrous webs (2-5). In nonwovens, for example, the permeability of the fibrous structure affects product behavior in processes such as liquid infiltration, rewet, and wicking, although such flows are also complicated by multiphase phenomena, especially surface tension effects.

In paper manufacturing, permeability can control the amount of water removal possible in a press nip. In impulse drying, a pressing process involving intense heat transfer from a heated roll, permeability is also expected to be of fundamental importance. Not only will permeability control the water removal ability of the impulse-dried sheet, as in standard wet pressing, but permeability will also directly affect the vapor phase that forms in the sheet, with low sheet permeability leading to higher internal vapor pressures and a greater tendency for delamination (sheet rupture due to internal vapor pressure). Details on the role of permeability in impulse drying and related water removal processes are given in (6-8).

Permeability is also of direct importance in drying operations, where it affects vapor flow and liquid flow driven by bulk pressure gradients (9). Permeability of the sheet to vapor can be a limiting factor in high-intensity drying operations (10).

Anisotropic permeability becomes an issue whenever two-dimensional fluid flows are possible in a web. Pressing operations are one example (11-13). Although the flow in a nip is primarily in the transverse direction, some in-plane flow components can exist. This in-plane flow becomes especially important when crushing occurs (14). The small in-plane flows can also contribute to economically significant reductions in water removal, depending on the anisotropic permeability of the sheet (15).

In-plane flows can also be important in blade coating, where a large pressure gradient in the machine direction exists under the blade (16). Penetration of the coating color can then involve both z-direction and lateral flows. Characterization of the process requires knowledge of the lateral permeability as well as the transverse permeability.

In-plane permeability can also be important in nonwoven products such as diapers and other absorbent products. In the broad area of textiles, measurements of in-plane permeability have been conducted for some time at TRI (17-20). These studies will be mentioned in more detail below.

Factors Affecting Permeability

The permeability behavior of a paper sheet is affected by numerous factors, including refining, yield, fines content, pH, and sheet formation. For example, Carlsson (21,22) and Ellis (23) found that permeability decreased with increased refining; high freeness pulp tends to have high permeability. Gren (24) examined the effect of cooking method and yield, finding in general that an increased kappa number or higher yield resulted in increased permeability to water.

Ellis observed a basis weight effect in which lightweight sheets had a higher permeability than expected. He speculated that this result was due to an end effect from the roughness of the porous tester plate which supported the sheet.

Another interesting feature observed by Ellis was an effect of consistency during formation. Sheets formed at low consistencies at which little fiber entanglement occurred in the stock tended to have lower permeability than sheets formed at higher consistencies where fiber flocs could form. Based on the figures Ellis presents, it appears that the high consistency sheets may have 2-4 times the permeability of sheets formed at low consistency.

Studies of Anisotropic Permeability

While much has been published about the z-direction or transverse permeability of paper (21-32), measurements of the lateral permeability components and their relation to transverse permeability have not been available in the literature. For lack of better information, those who have dealt with two-dimensional flows in paper have tended to assume that the permeability of paper was uniform in all directions (1,4,33), even though paper is an obviously anisotropic material.

permeabilities. Significant differences in press performance for felts with similar transverse permeabilities but dissimilar lateral permeabilities suggested that two-dimensional flow in felts plays an important role in wet pressing. Chevalier (41) has also reported measurements for directional permeability in felts, finding in-plane permeabilities on the order of 2-3 times the transverse permeability.

To explore basic issues about the anisotropic permeability of paper, a project was launched at The Institute of Paper Chemistry in 1987. Early results have been published by Lindsay (42,43), who measured the transverse, cross-direction, and machine-direction permeability components in several paper samples. In the few samples which were examined, the ratio of average lateral to transverse permeability ranged from roughly 2 to 10, which was larger than predicted by simple models of flow over oriented cylindrical rods (44,45), but consistent with data from Adams (39) for textiles, where ratios of 2 to 5 were reported.

The ratio of machine-direction to cross-direction permeability was also obtained in several paper samples (46), with values generally in the range of 1 to 2 and frequently in the range of 1.1 to 1.3. In a related study by Horstmann et al. at IPST (47), a new experimental method to characterize edge penetration in photographic papers was used to provide information on anisotropic in-plane permeability. Measurements in five similar samples of uncompressed photographic paper again showed MD-CD permeability ratios in the range of 1.1 to 1.3. Transverse permeability was not measured.

EXPERIMENTAL APPROACH

Equipment

Lateral permeability. The basic experimental procedure has been previously described (42,43,48). Figure 1 shows the apparatus for lateral permeability measurements in saturated sheets. A modified Carver press with an air bag assembly allows paper to be pressed between two platens. The lower platen has an 0.56-cm hole at the center through which fluid is injected. Fluid is driven into the port by regulated compressed air above the fluid meniscus in the line. Flow rates are determined by tracking the fluid meniscus in the translucent tubing.

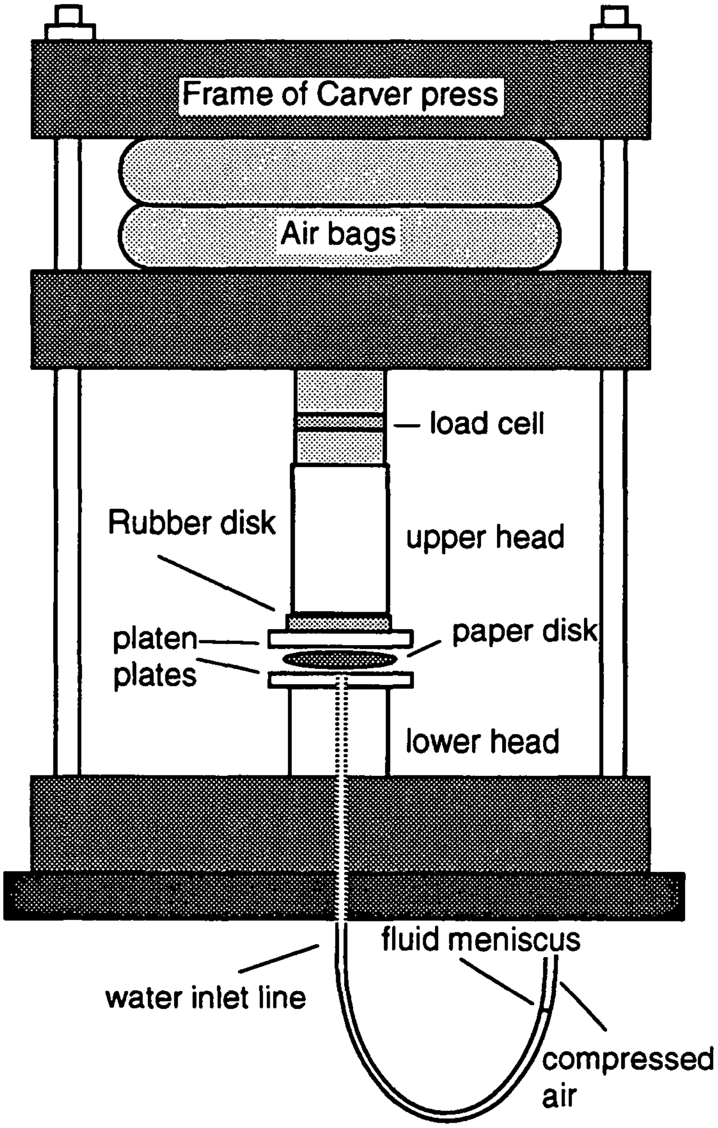

Figure 1. Schematic of the lateral permeability setup.

After a saturated paper disk is placed between the two platens, pressure is applied to provide a seal between the paper surfaces and the platens. Fluid in the tubing line is then pneumatically driven into the paper. The fluid flowing into the injection port enters the paper and is forced to flow radially outward through the paper itself. If the applied load is uniform and the sheet itself is uniform in thickness, then channeling flow between the sheet and the platens is avoided. This was verified by observing the location of dyed fluid injected into sheets.

The thickness of the paper disk during lateral permeability measurements was measured with a set of linear variable displacement transducers (LVDTs) embedded at 120° intervals around the edge of the lower platen, with sensor armatures mounted on the upper platen.

The average lateral permeability is expressed in terms of measured parameters:

$$K_r \equiv \frac{K_x+K_y}{2} = \frac{Q\,\mu\,\ln(R_o/R_i)}{2\pi\,L\,\Delta P}, \qquad (2)$$

where Q is the volumetric flow rate based on the motion of the meniscus in the supply tubing, R_o is the outer radius of the sheet, R_i is the radius of the injection port, L is the sheet thickness, and ΔP is the pressure drop from the injection port to the edge of the sheet. Details of this solution are given in (47). While Equation 2 is based on a simplification of the flow problem, numerical analysis has indicated that it can be applied with reasonable accuracy (46).

Transverse permeability. The equipment used to measure transverse permeability also uses the Carver press frame and is shown in Figure 2. The basic features of the equipment have been previously reported (42,43,46).

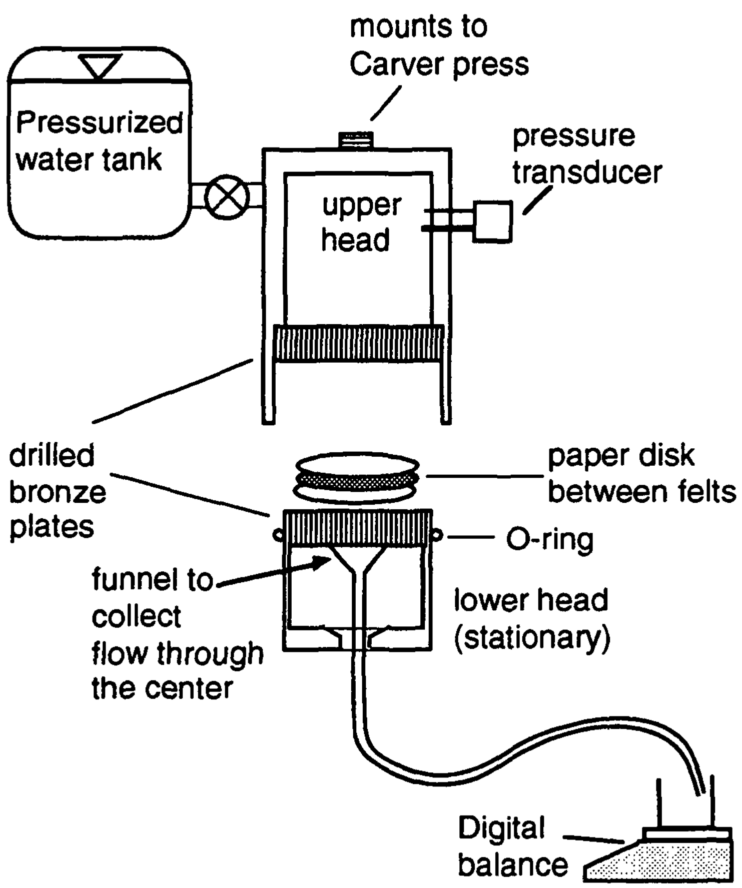

Figure 2. Schematic of the water flow system for transverse permeability measurements.

In making transverse permeability measurements, a saturated paper disk is compressed between two wet felts. The felts are in contact with finely drilled bronze plates that transmit mechanical pressure while allowing water to flow through. Carbon paper imprints taken under load confirmed that the felts were adequate in generating a uniform load across the paper.

To eliminate problems with leakage around the edge of the paper, only the flow through the central region (comprising 23% of the area of the paper disk) was collected and measured. This fluid entered a funnel which led the fluid through plastic tubing to a graduated cylinder below the Carver press assembly. Others have used compression rings around the edge of the sample to prevent edge flows. The present method allows compressibility data to be obtained while measuring permeability (with compression rings, the mechanical load experienced by the bulk of the sheet is unknown) and makes it easier to have uniform pressure across a sheet.

Sheet thickness was obtained using a Kaman eddy-current transducer (ECT). By measuring the position of the upper head while compressing two felts alone and then while compressing the two felts plus paper, the thickness of the sheet could be obtained from the difference. Cubic regression of the thickness-versus-load data was done for the felts before and after each run. The accuracy of the thickness measurement is estimated to be ± 9 μm (0.35 mils). Further details are given in (43). Given the inherent uncertainties in defining paper thickness, this error is acceptable.

In transverse permeability measurements, water passes through the central region of the paper and felts with a known pressure drop. The permeability is given by:

$$K_z = \frac{L}{\frac{A_{flow}\,\Delta P}{Q\,\mu} - R_f}, \tag{3}$$

where A_{flow} is the cross-sectional area of the flow collection region (23% of the sheet area) and R_f is the inherent resistance of the felts and flow system. R_f was usually of little importance since the paper resistance was so much greater than the resistance of the felts or other components of the flow system.

The use of press felts to distribute load and permit flow offers several advantages over rigid media, such as sintered metal plates, which offset the disadvantage of having to calibrate felt thickness as a function of load. The compressibility of felts makes it much easier to apply a uniform mechanical load, even when nonuniformities exist in the sample. The low flow resistance and high load uniformity of felts are not easily matched with available rigid media.

Porosity

Porosity, ε, or void fraction (volume fraction of water), is obtained from the sheet thickness and dry weight:

$$\varepsilon = 1 - \frac{m}{A\,L\,\rho_c} \tag{4}$$

where m is the oven-dry mass of the sheet, A is the planar area, and ρ_c is the density of cellulose, 1,550 kg/m^3. This standard engineering definition of porosity is dimensionless, whereas a variety of industrial tests of paper properties yield 'porosity' values in terms of dimensional quantities such as flow rates of air.

Sheet Preparation

Most of the sheets in this study were formed from two pulp types, a bleached southern softwood kraft and bleached southern hardwood kraft. In addition, some tests were done with unbleached southern softwood kraft, unbleached northern softwood kraft, and bleached northern hardwood kraft. Paper samples were formed on British handsheet molds or, in the case of the unbleached kraft pulps only, as samples cut from a wet web produced on a flow spreader. For handsheets, stock preparation was done according to TAPPI procedures, except that some pulp samples were over disintegrated (150,000 revolutions instead of the standard 50,000). Most pulp was unrefined, although light refining with a PFI mill was done for several samples to vary freeness.

Wet handsheets were prepared from pulp samples using standard TAPPI method T205 om-88 (49) with several exceptions. The newly formed handsheets were only lightly pressed (70 kPa for 1 minute instead of 345 kPa for 5 minutes) to maintain high saturation (20-25% solids). Some sheets at higher solids levels (ca. 50%) were obtained by pressing at 345 kPa for 3 minutes.

A wide variety of handsheets were tested. Most of the work was done with bleached kraft pulps, with the various classes listed in Table 1. Bleached pulp types included southern softwood (SSW), southern hardwood (SHW), and northern hardwood (NHW). Mechanical treatments included Tappi standard (S), over-disintegration (OD), and PFI-mill refining in addition to standard disintegration (PFI). Three wires of differing mesh size were used in the British handsheet former; wires 1 and 3 were 150 mesh and wire 2 was 100 mesh. Because earlier work gave some evidence of permeability changes with storage time of pulp, the effect of aging was examined by comparing sheets made with fresh pulp with those made from the same pulp after five weeks of storage in a cold room. Pulp was stored with some added formaldehyde to prevent microbial degradation.

Table 1. Different classes of sheets made from bleached pulp.

Pulp	B. Wt., gsm	Mech. Treat.	Wire	Age	Other
SSW	135	S	1	Fresh	
SSW	270	S	1	Fresh	
SSW	145	S	2	Fresh	
SSW	300	S	2	Fresh	
SHW	135	S	1	Fresh	
SHW	270	S	1	Fresh	
SHW	100	S	2	Fresh	
SHW	200	S	2	Fresh	
SSW	135	OD	1	Fresh	
SSW	270	OD	1	Fresh	
SHW	135	OD	1	Fresh	
SHW	285	OD	1	Fresh	
SSW	135	PFI	1	Fresh	
SSW	270	PFI	1	Fresh	
SHW	135	PFI	1	Fresh	
SHW	270	PFI	1	Fresh	
SSW	135	S	1	Fresh	100% solids
SSW	135	S	1	Fresh	50% solids
NHW	135	S	1	Aged	
SSW	135	S	1		Recy-cled
SSW	400	S	3	Aged	
SSW	270	S	3	Aged	
SSW	135	S	3	Aged	
SHW	270	S	3	Aged	

In addition to the bleached pulp samples, measurements were also made in several unbleached kraft sheets from both northern and southern softwoods. Two different freeness levels were examined, 550 and 650 CSF, with freeness varied by refining in a Valley beater.

Run Procedures

Transverse permeability. In transverse permeability measurements, 7.6-cm paper disks cut from wet handsheets were placed between two wet felts. The thickness of the felts as a function of load was measured before and after each run. The felt and paper were placed on top of the lower drilled bronze disk, then the hydraulics of the system were used to lower the upper head. A valve was opened to allow deaerated water to fill the upper chamber and to begin flowing through the felts and paper. The air line to the air bag was adjusted to achieve a specified load on the paper, as read from an LCD meter connected to a load cell. An initial mechanical pressure of about 200 kPa was applied. Several readings of flow rate and sheet thickness were made over 2-4 minutes, whereupon the mechanical load was increased and more measurements were made. As mechanical load was increased, sheet permeability decreased and longer flow sampling times were needed for accurate measurements. Maximum applied pressures were often near 700 kPa.

Lateral permeability. Saturated 7.6-cm disks cut from handsheets were again used and placed on the lower platen containing an injection port. The injection port and injection line were previously filled with fluid. The upper platen was placed on the sheet, guided by two guideposts to ensure that the LVDT armatures were properly centered in the sensor cores. Mechanical pressure was applied through the airbag assembly, beginning with about 200 kPa and gradually increasing to 700 or 800 kPa. At each mechanical load, the distance traveled by the air-liquid meniscus in the injection line was tracked in time to obtain the flow rate. LVDT readings were recorded to give sheet thickness. LVDT's were calibrated daily. Occasional tests checked the pressure uniformity and flow symmetry about the injection port.

RESULTS

A large set of data was collected in this phase of the permeability study. Representative data are presented below. Permeability values are typically plotted against porosity, which is the fractional volume of the sheet occupied by water as defined in Equation 4 above. The porosity range shown depends on the compressibility of the sheet over the applied mechanical pressure interval. The high porosity data points are typically at mechanical pressures of 200 kPa, and the low porosity data were typically obtained near 700 kPa. When sheets were compressed during a transverse permeability run and then later subjected to a lateral permeability test, the first compression cycle caused some permanent deformation, resulting in lower porosities at a given load. However, replicate tests showed that the permeability-porosity relationship was unchanged after undergoing a cycle of compression as long as the sheet was kept saturated.

Anisotropy

Results of the present study confirms the observation in earlier IPST work that in-plane permeability tends to be much greater than transverse permeability. Figures 3 and 4 show typical anisotropy in bleached softwood sheets, with ratios of lateral to transverse permeability on the order of 5-10. Figure 5 shows similar results in hardwood sheets. Figure 6 shows an example of data revealing extremely high anisotropy ratios, with lateral permeability around 40 times as high as transverse permeability. Measurements in handsheets from the bleached northern hardwood sheets also showed high anisotropy, as indicated in Figure 7.

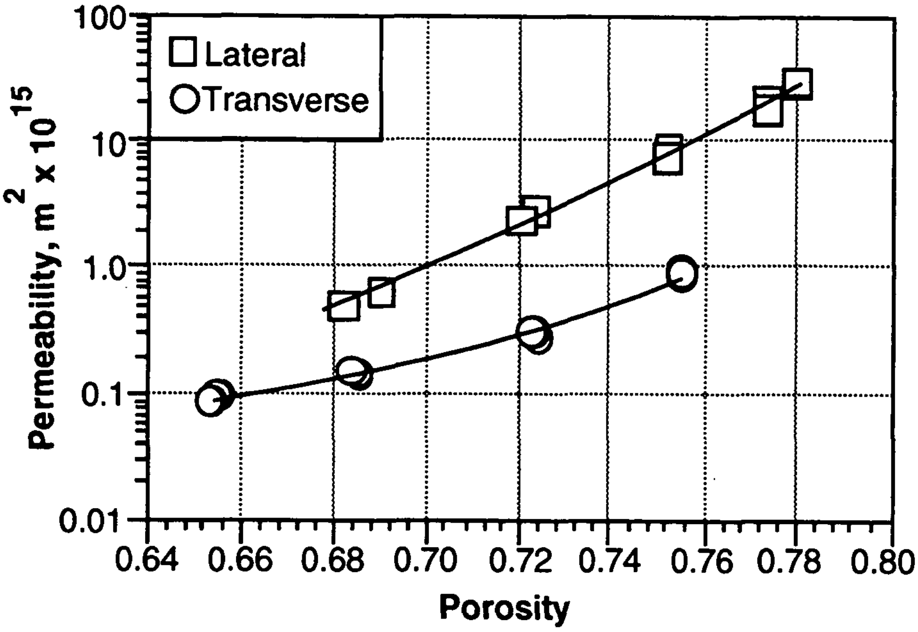

Figure 3. Anisotropy in 300 gsm bleached southern softwood sheets (two separate sheets used), 715 CSF.

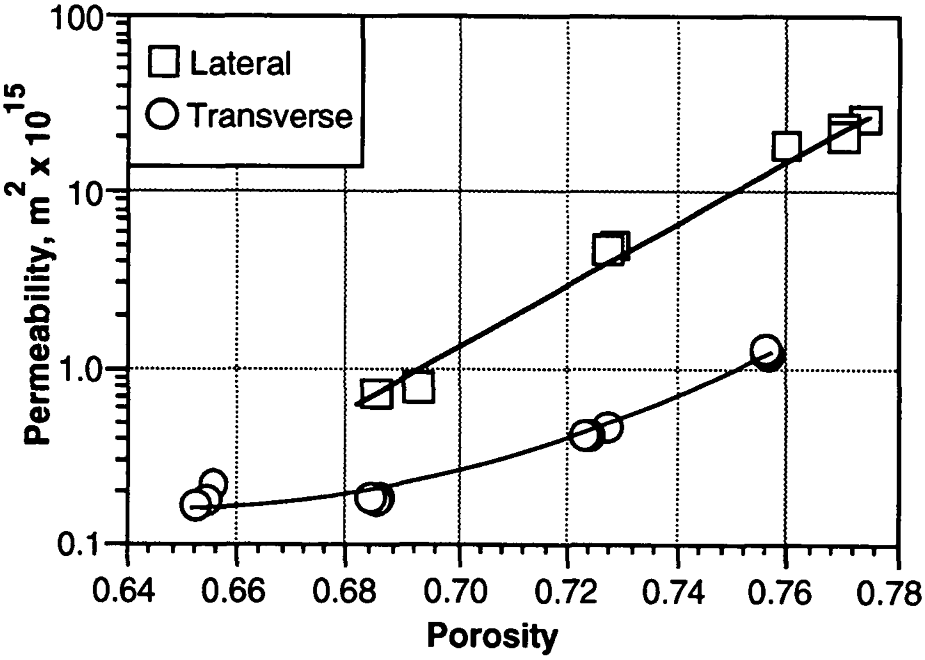

Figure 4. Anisotropy in 270 gsm bleached softwood sheets (two separate sheets used), 715 CSF.

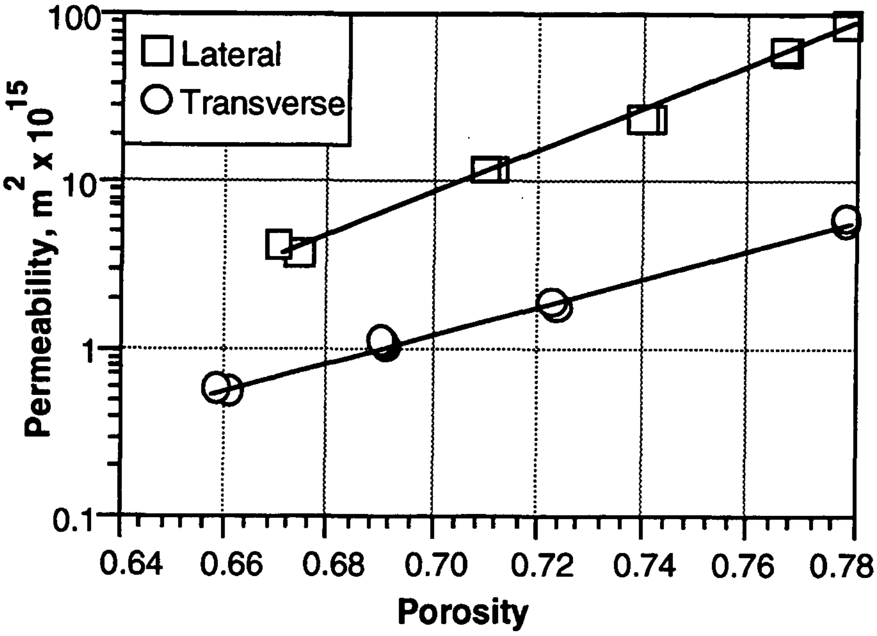

Figure 5. Anisotropy in 270 gsm bleached hardwood sheets (two separate sheets used), 653 CSF.

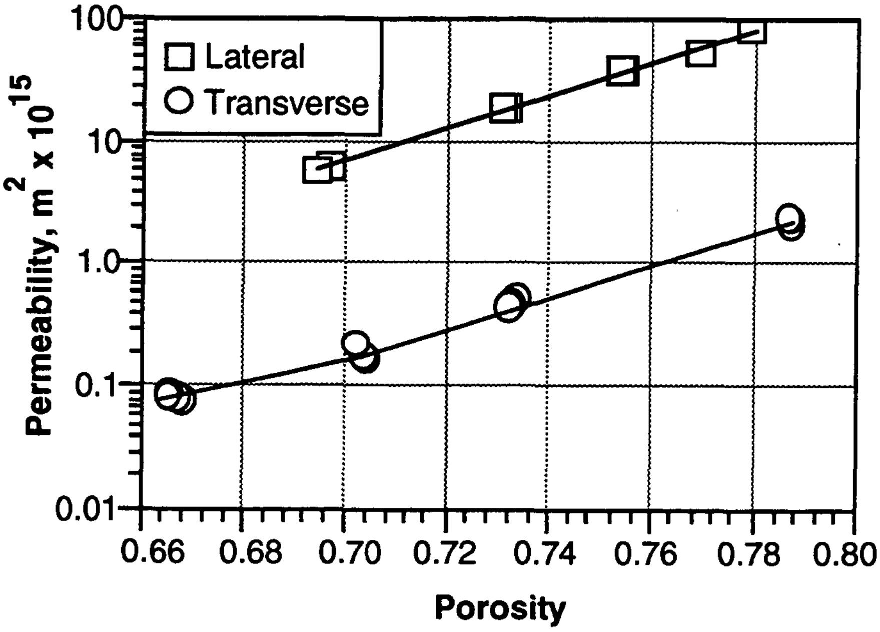

Figure 6. High anisotropy in a 270 gsm bleached hardwood handsheet, 581 CSF.

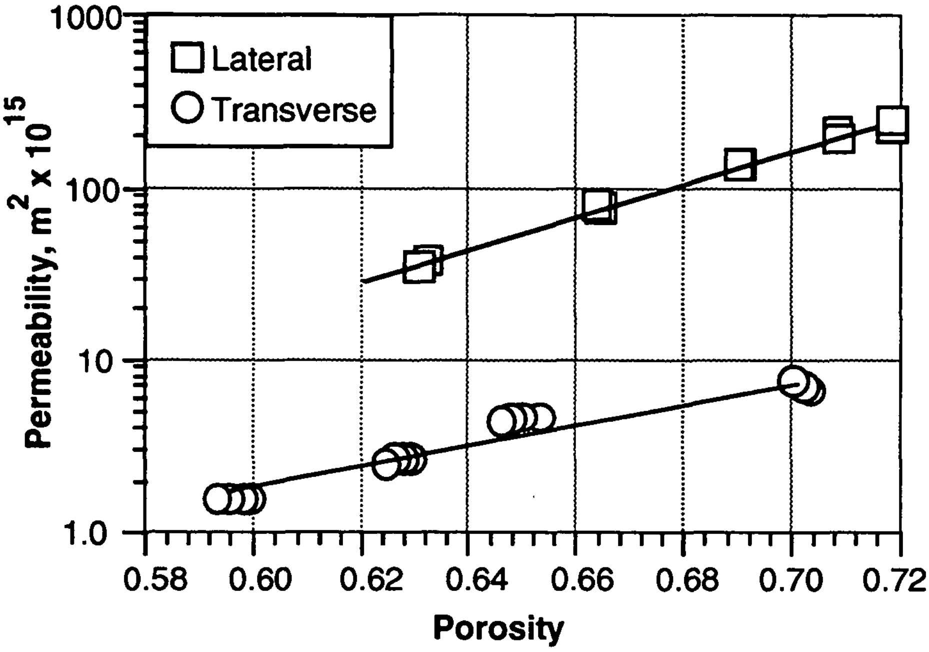

Figure 7. High anisotropy in a bleached northern hardwood pulp, 665 CSF, 135 gsm sheet.

Data for unbleached softwood sheets are given in Figure 8, where anisotropy ratios on the order of 2-4 are found. Early measurements in unbleached softwood from this study also found anisotropy ratios of 2-4. However, much higher anisotropy in unbleached softwood kraft sheets is sometimes observed, as shown in Figure 9. Anisotropy is expected to be affected by details of sheet formation as well as intrinsic fiber properties. The unbleached sheets used in this study were formed on a low-velocity flow spreader that probably imparted a different formation and pore structure than a handsheet former.

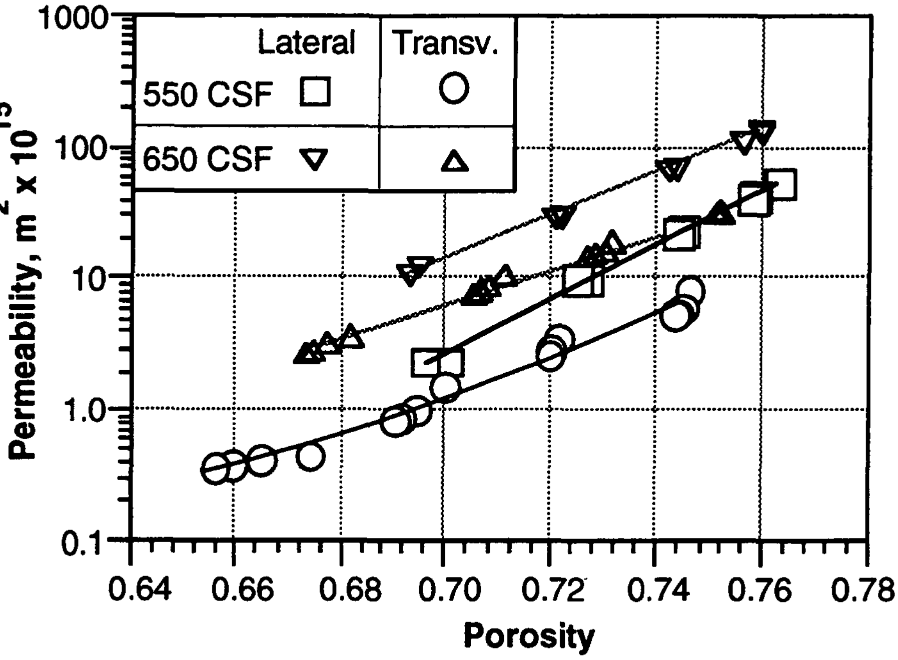

Figure 8. Lateral and transverse permeability measurements in two sheets of unbleached southern softwood kraft at freeness levels of 550 and 650 CSF. Initial solids 41%.

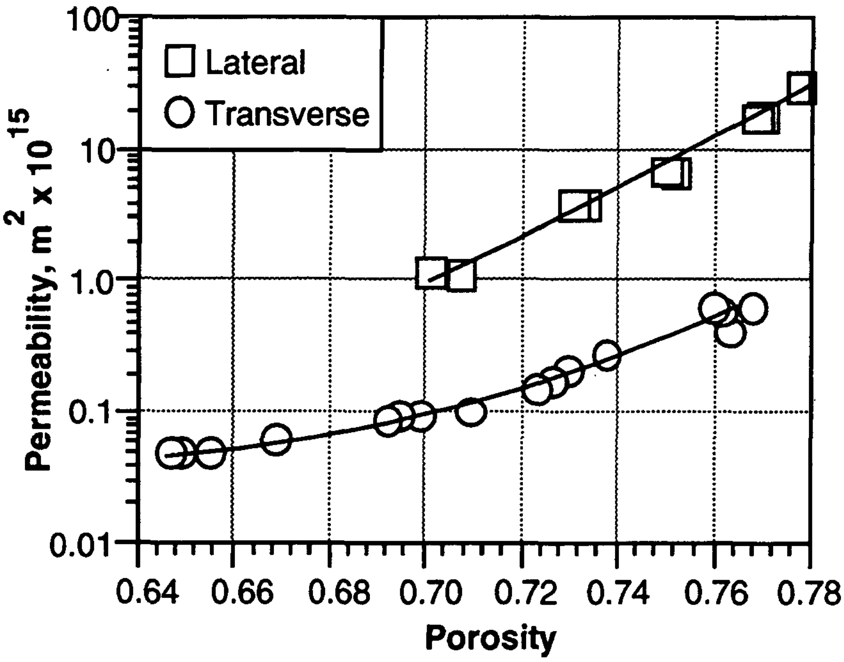

Figure 9. High anisotropy in a 200 gsm unbleached southern softwood handsheet, 650 CSF, 35% solids initially.

High anisotropy has also been observed in unbleached TMP handsheets in previous measurements from this study (43), as shown in Figure 10. Anisotropy ratios (lateral permeability divided by the average in-plane permeability) were often on the order of 10-20 for TMP samples of all basis weights.

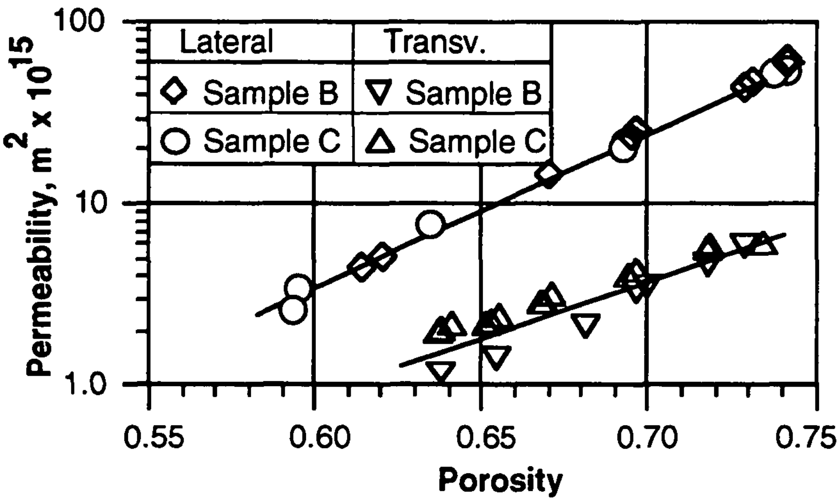

Figure 10. Anisotropic permeability in two sheets of 200-gsm TMP.

The finding of high anisotropy in sheets from various pulp types suggests that the inherent pore structure in a fibrous web such as paper has larger channels in the plane than in the z-direction. This has ramifications for water removal operations in which two-dimensional flow may be possible, as discussed below.

Freeness and Permeability

An important result from this study concerns the danger of relying on freeness as a measure of permeability or water removal capability of a sheet. Measurements of Canadian Standard Freeness are commonly assumed to give information on the water removal properties of a pulp, and this assumption is true, to a degree. For a given pulp type, mechanical treatments which reduce CSF will also usually reduce permeability and thus hinder water removal in pressing and drying operations. However, the relationship between permeability and freeness is not only nonlinear and different for each pulp type; it is also path-dependent, meaning that different treatments to achieve a given freeness level may result in different permeabilities. In other words, CSF may be a poor measure of water removal behavior.

Figure 11 demonstrates the path-dependent relationship between freeness and transverse permeability in 270 gsm bleached southern softwood sheets. (Unless otherwise specified, permeability data presented from this point on refer to transverse permeability.) Over-disintegration (three times the Tappi standard) and PFI refining of the same pulp, initially 715 CSF, resulted in two different freeness values but virtually the same permeability. The difference in freeness between the two treated samples is less than the difference in freeness between the original pulp and the over-disintegrated pulp. The same effect is shown for 135 gsm sheets in Figure 12. Hardwood fibers responded in the same way, as shown in Figure 13.

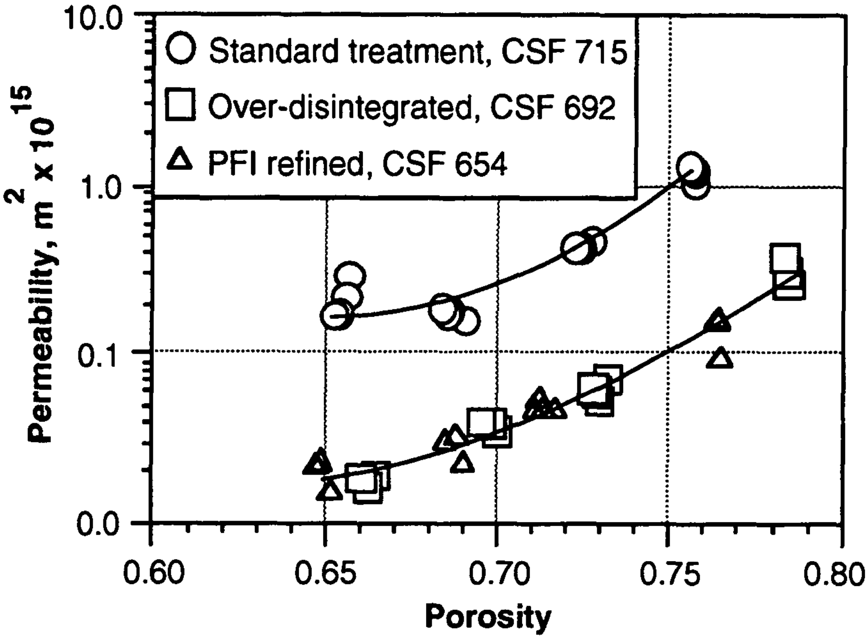

Figure 11. Transverse permeability of bleached softwood sheets, 270 gsm, after various mechanical treatments to the pulp.

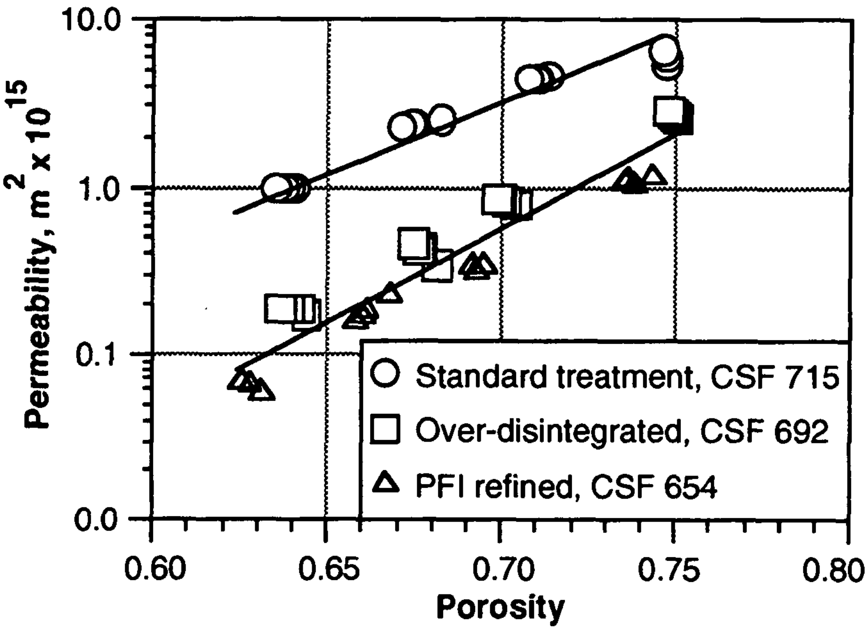

Figure 12. Permeability of bleached softwood sheets, 135 gsm, after mechanical treatments to the pulp.

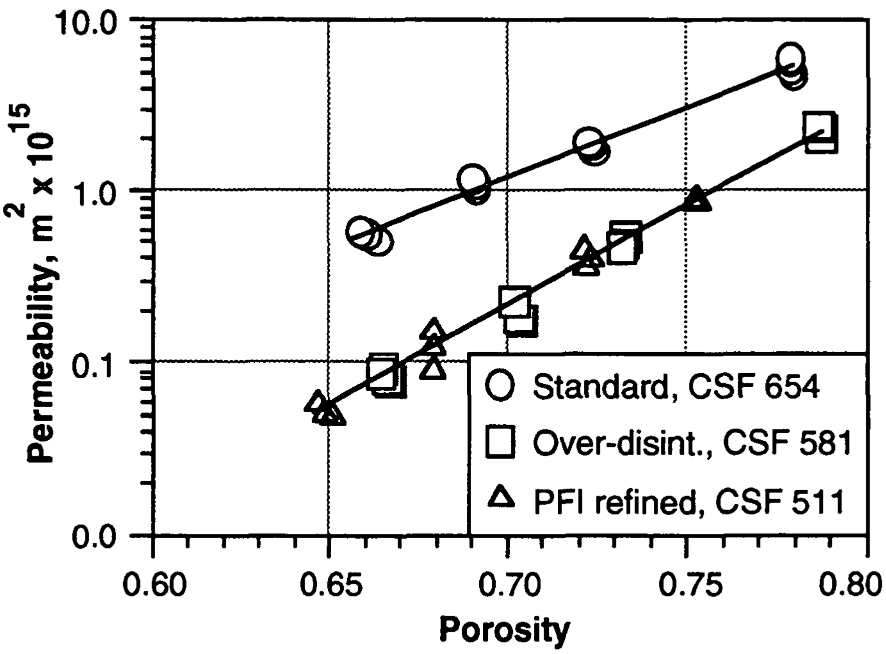

Figure 13. Permeability of bleached hardwood sheets, 270 gsm, after various mechanical treatments to the pulp.

Small changes in freeness may cause large changes in permeability. For example, a reduction in freeness from 700 to 500 may correspond to a permeability change of two orders in magnitude. Permeability appears to be a more sensitive parameter than freeness, in addition to being more useful in describing water removal behavior. Freeness, however, is likely to be more useful than permeability in describing drainage behavior on a wire.

Permeability, freeness, and impulse drying behavior. During this study, we were asked by David Orloff of IPST to examine the permeability of some papers that had given somewhat perplexing behavior during impulse drying. Sheets from two supposedly similar pulps (both unbleached kraft softwood with the same CSF values) had remarkably different behaviors during impulse drying. One dewatered easily, showing remarkable potential in impulse drying. The other delaminated, meaning that internal vapor pressure generated by contact with the hot rolls caused the sheet to blister and even blow apart as it left the nip. Unfortunately, the first pulp type was used in early tests of impulse drying, leading to great enthusiasm for the process (50), while the other pulp type was used in industrial pilot testing, leading to serious apprehensions (51).

These results were perplexing until permeability was measured. The pulp that delaminated easily had a much lower transverse permeability, as shown in Figure 14, although both pulps had the same freeness. The low permeability pulp also had a lower kappa number, so differences in cooking probably contributed to the lower permeability. According to our current understanding of impulse drying physics, a low permeability results in high vapor pressure build-up in the sheet, and the pressurized vapor is not easily vented through the low-permeability web as the sheet leaves the nip. As a result, pressure forces in the sheet can then cause delamination.

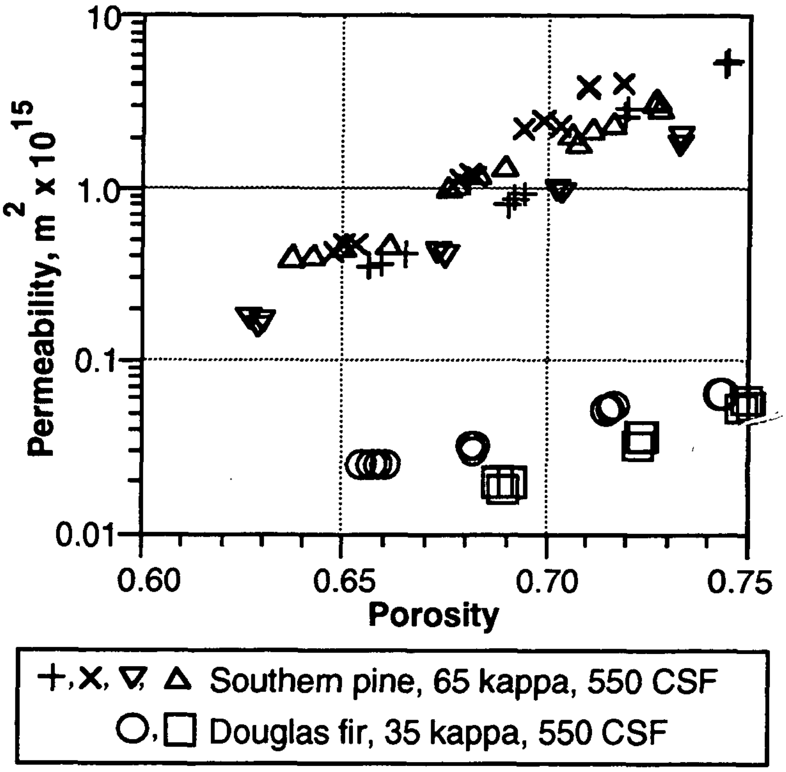

Figure 14. Differences in transverse permeability between two unbleached softwood pulps at the same freeness. Results for several sheets are shown.

In Part II of this paper, we will discuss the causes of anisotropic permeability and the consider the ramifications for papermaking processes. We will also present additional data relevant to fiber-water interactions in recycling, the effect of fines, and the role of macropores in z-direction permeability.

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